Cylindrical Ferro Electric Generators Waveshaping Techniques and Performance

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Abstract

This paper will review a current research and development effort aimed at developing a small form factor cylindrical PZT Ferro Electric Generator (FEG). Two options will be discussed – shaping the PZT crystal into a conic section and shaping the acoustic pulse from the explosive wave train, both techniques will be discussed in terms of ease of implementation, fabrication and performance achieved. We will also discuss corona induced failure in FEG devices and methods to mitigate this effect. Representative data will be presented for FEG devices made from EC-64 and 95/5 PZT for both geometries. Scaling relations will be presented and discussed in terms of physical dimensions and materials.

I. INTRODUCTION

The generation of electrical pulses due to pressure induced effects in PZT materials has been studied for several decades. Much of this work has focused on geometries such as bars and disks that have been impulsively loaded by a variety of sources including light gas guns, various mechanical compression techniques, and with explosives. The varieties of geometries and pressurization methods produced a large data base that laid the foundation for the current generation of ferroelectric generator (FEG) technology (1,2,3,4,5). Recently improvements in PZT mixtures and production techniques have led to the availability of a high energy compound 95-5 that was used as a material for this work (2). This work describes a departure from the bar and disk geometries of past work to FEG pulse generators based on cylindrical/conical structures. Cylindrical or conical structures offer favorable scaling since the surface area and volume of the material scale with the radius squared and height of the structure and with suitable wave shaping, allows large areas and volumes to be utilized in the FEG. With the addition of pressure wave shaping, these geometrical structures minimize the amount of explosive needed for excitation.

In our laboratory, we have developed these techniques to a reliable, simple pulse generator capable of producing large electrical pulses in a small compact geometry.

II. EXPERIMENTAL

The final designs for the cylindrical FEG pulse generator involved an evolutionary process and a series of experiments to determine best practices. Inherent in the idea is the fact that the pressure wave expanding from the detonation of a linear “rope” explosive charge has cylindrical symmetry and evolves into a uniform expanding conical pressure wave as the explosive detonates along its length. Previous research efforts with FEG’s show that it is desirable to place the surface of the PZT material under pressure simultaneously (1). Two options exist for accomplishing this. The first is to shape the PZT element into a conic section with the cone angle determined by the detonation properties of the explosive and second is to shape the explosive charge to produce a planar expanding wave front while maintaining a cylindrical/ring shape for the PZT. We investigated both these techniques in this work.

A. Initial Experiments with Cylindrical Samples

The first series of experiments were aimed at testing the potting process and to determine if there were any issues with corona at the PZT-metallization interface. The initial devices were built using off-the-shelf readily available EC-64 PZT elements as shown in figure 1.

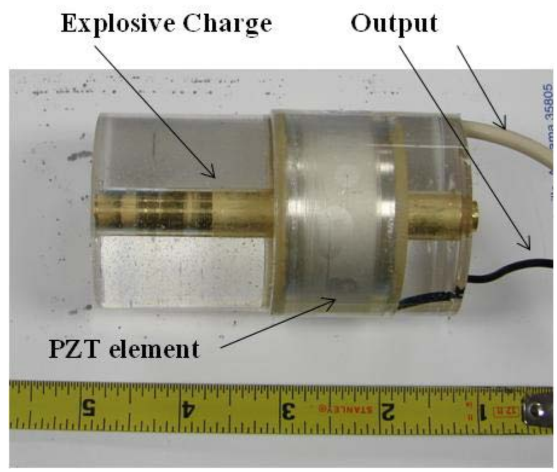


Figure 1. Photograph of initial PZT test article. The PZT element is a cylindrical shell with dimensions of 44 mm OD, 38 mm ID, and 30 mm high.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2011	**N/A**	**-**

4. TITLE AND SUBTITLE
Cylindrical Ferro Electric Generators Waveshaping Techniques and Performance

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Radiance Technologies; AMRDEC

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT
This paper will review a current research and development effort aimed at developing a small form factor cylindrical PZT Ferro Electric Generator (FEG). Two options will be discussed shaping the PZT crystal into a conic section and shaping the acoustic pulse from the explosive wave train, both techniques will be discussed in terms of ease of implementation, fabrication and performance achieved. We will also discuss corona induced failure in FEG devices and methods to mitigate this effect. Representative data will be presented for FEG devices made from EC-64 and 95/5 PZT for both geometries. Scaling relations will be presented and discussed in terms of physical dimensions and materials.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**5**	

As shown in figure 1, the explosive charge, the cylindrical shell PZT and output tabs were potted in a cylindrical mold using a clear potting compound. Since the process is exothermic, it was necessary to develop a process to eliminate gas bubbles and thermal expansion effects in the potting process. Examination of the voltage-time traces showed anomalies that were not consistent with past experiments as described in references 1-5. For all our testing, we used C-4 explosives. There were two possible reasons for the anomalies. First, as the detonation of the explosive charge proceeds, the pressure wave progresses through the potting compound at an angle determined by the pressure wave velocity in the potting compound and the detonation velocity of the explosive. As a result, the pressure wave does not arrive planar to the crystal surface and it is possible that the pressure pulse has transited part of the crystal while the far end has yet to see the pressure pulse. Second, it is possible that there is corona around the metallization-potting compound interface that influences the magnitude of the voltage generated. A high speed framing camera was used to observe the process as shown in figure 2.

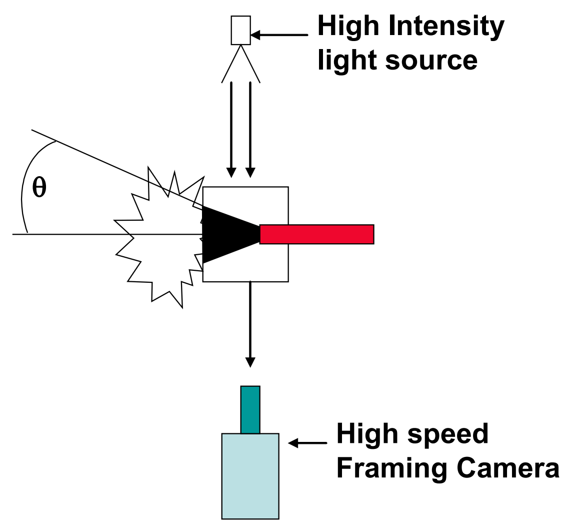
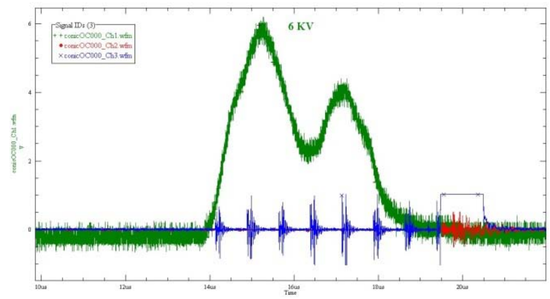
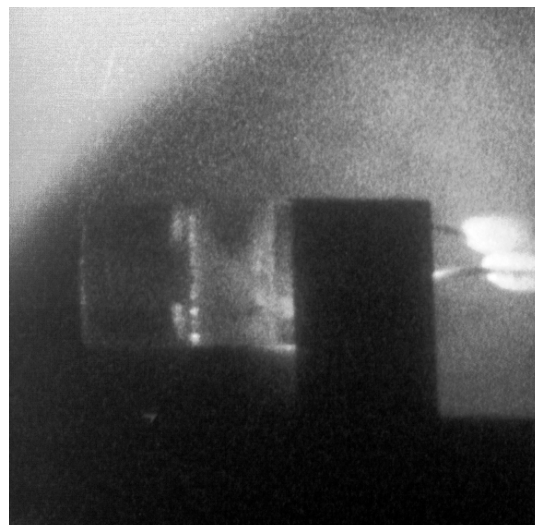


Figure 2. Diagram of experiment to observe FEG pulse generators shown in figure 1

The electrical diagnostic and the camera frame rate were correlated so that optical phenomena could be directly related with the measured voltage- time trace. This work was done at the University of Alabama Hypervelocity Impact Facility in Huntsville, AL. Figure 3a shows a typical voltage-time trace with anomalies. Superimposed on the trace and synchronized with it, is the trigger signals sent to the framing camera. Note that figure 3b shows typical corona at the metallization-potting compound interface. The corona shown is typical and observed in all initial experiments.



(a)



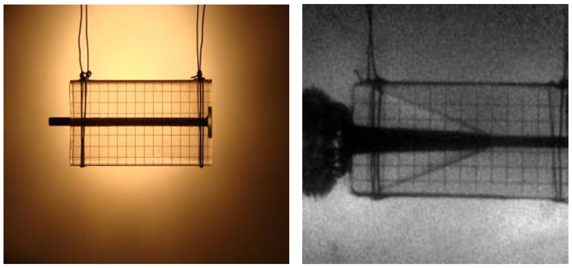
(b)

Figure 3. (a) voltage-time trace from a typical device shown in figure 1. Note superposition of camera trigger signals. (b) Photo of FEG showing massive corona on both ends of the metallization.

Prior to further experimentation, changes in the potting and curing process were implemented that practically eliminated any bubble formation within the potting compound and in subsequent experiments, we were able to completely suppress the corona by painting the metallization with a corona suppressing paint prior to potting. As a result, reliable and repeatable performance was achieved in these preliminary experiments.

B. Characterization of Expanding Pressure Wave

Using the experimental set-up shown in figure 2, test blocks of the potting compound containing the explosive charge were fabricated for testing in the same facility. Figure 4a is a "still" back lighted photograph, showing the geometric arrangement of all elements and the 1 cm grid etched into the backside of the block.

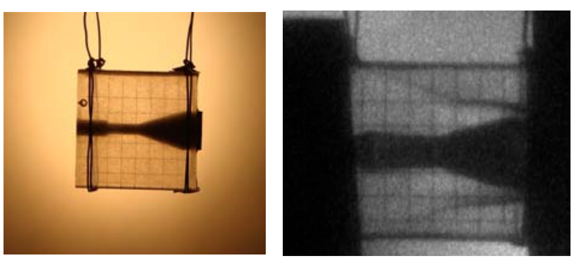


(a) **(b)**

Figure 4. Photographs from the experiments to determine the characteristics of the expanding pressure pulse from the linear explosive charge. (a) still photo showing elements. (b) same sample after detonation at left end. Note that detonation has progressed about half way down the sample.

In figure 4b, note that the expanding shock/pressure pulse is clearly visible due to the pressure induced changes in the optical properties of the potting compound. The measured cone half-angle is about 22 degrees for this explosive and potting compound.

Examination of figure 4 leads to the conclusion that a conical explosive charge with the same half-angle will produce a planar expanding pressure pulse at the interface between the potting compound and the PZT. Figure 5 shows that experiment.



(a) **(b)**

Figure 5. Photographs from the experiments to determine the characteristics of the expanding pressure pulse from the linear explosive charge. (a) still photo showing elements with conic explosive charge. (b) same sample after detonation at left end. Note planar pressure front at right.

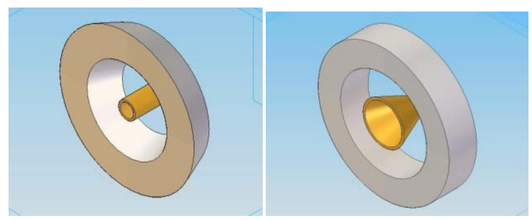
Clearly, the experimenter has the option of shaping the PZT crystal into a conic section or shaping the explosive to produce a planar front at a cylindrical shell PZT crystal. In both geometries, the pressure pulse from the explosive would strike the inside surface of PZT as a planar front.

With the data obtained from this testing and shock modeling, we designed and built a next generation of optimized FEG's that are easy to construct, robust and inexpensive.

III. FEG DESIGN AND TESTING

A. FEG Design Considerations

Based on the experiments designed to determine the characteristics of the expanding pressure wave from linear explosive charges, two possible concepts emerged to develop explosive-on-axis FEG's. These concepts are shown in figure 6. Figure 6a shows a conic PZT element with linear explosive charge and figure 6b shows a similar arrangement with conic explosive charge and linear cylindrical shell PZT element. Both geometries in principle could be poled with the polarization vector either parallel or perpendicular to the axis of the PZT element.



(a) **(b)**

Figure 6. Possible configurations for FEG's based on pressure wave shaping. (a) conic section FEG with linear explosive charge. (b) Cylindrical FEG with conic section explosive charge.

Both designs require a specific pressure for optimal operation. Therefore the distances from the explosive to ID of the PZT must be either modeled or measured to fall into an optimum range of 2-3 GPa. It should be noted that the angles and spacing's required for optimum operation of these FEG will be specific to potting material, explosive, and PZT type. In both cases, the area and volume of the PZT element scales favorably with radius and height allowing easy pressurization of large area and volume samples. In the course of optimization, we built and tested both designs in open circuit and into capacitive loads.

Working with TRS Technologies, Inc., State College, PA, we produced 95-5 PZT crystals in three polarization geometries. The conic crystals were poled with the polarization vector normal to the inner surface, at an angle with respect to the cone angle. For the cylindrical shell crystals, polarization vectors parallel to the shell axis, designated rings, with metallization on the ends of the shell and as cylinders with polarization perpendicular to the shell axis. In this case, the metallization is on the inner and outer surfaces of the crystals. All designs have been tested.

B. Conic FEG

The initial testing of the conic 95-5 PZT crystals used the cone angle determined from the explosive experiments shown in figure 4. These efforts were only partially successful due to sintering and poling problems. As a result of a development effort at TRS, we received 6 units. When the PZT elements were made into FEG's and tested, only half of the samples produced any measurable output at all. The other three while producing measurable output, produced only a fraction of what it should be. Consequently, we decided to concentrate instead on the development of cylindrical FEG's with shaped explosive power train. Figure 7 shows the results from the conic PZT test. We are uncertain why the wave shape is asymmetric and why the output is far lower than expected.

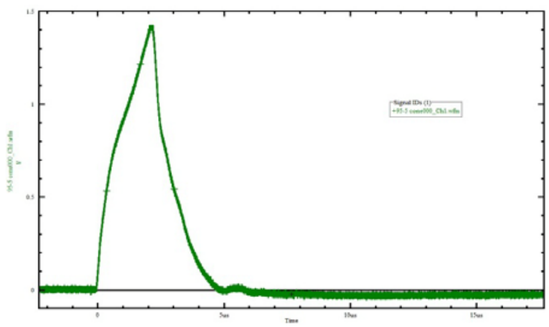


Figure 7. Wave trace from a conic FEG test

C. Cylindrical FEG's

The second set or FEG's were made using the PZT cylindrical shells, poled as either cylinders or rings as described above. The samples were 48 mm OD, 32 mm ID, and 10 mm high. All tests were conducted using conic explosive cores for pressure pulse wave shaping. FEG's poled as cylinders functioned quite well and produced voltage-time waveforms consistent with other published results. For the size chosen, the rise time observed, approximately 2 microseconds, correlated with the transit time of the pressure pulse through the PZT element. Figure 8 shows a typical waveform.

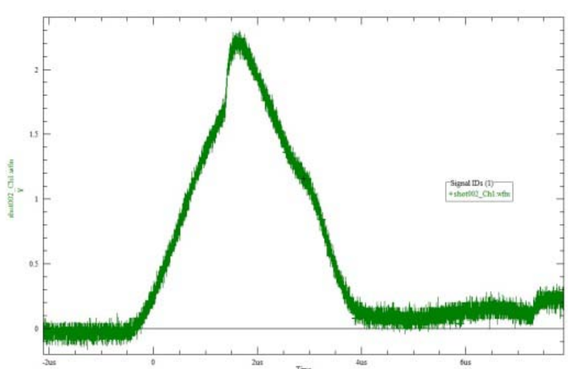


Figure 8. Wave trace from a cylindrical FEG test

These devices performed at approximately 75% voltage level when compared to the PZT devices poled in the "ring" geometry described below.

The final cylindrical shell geometry FEG design is identical to that just described except the polarization vector is now parallel to the shell axis and in the accepted nomenclature is in the "ring" geometry. The measured performance of these FEG's is excellent and highly repeatable. In fact, these devices performed the best of all the units we have tested to date and now constitute our standard for future development. They have sub-microsecond rise times and the highest recorded voltages of all of our test articles. Figure 9 shows a typical wave trace from one of our experiments. The wave shape, rise time, and voltage are similar to 95-5 data demonstrated by others in the field (2, 4).

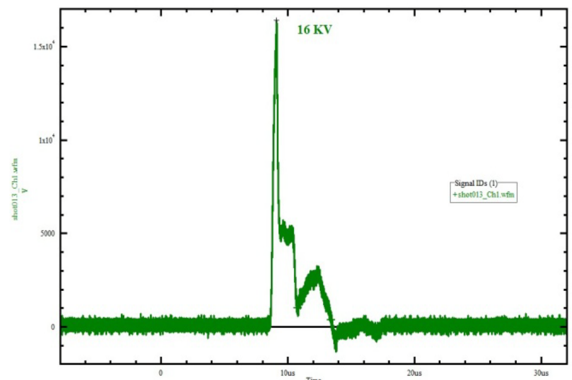


Figure 9. Wave trace from a ring FEG test

IV. SCALING RELATIONS AND ENERGIES

The most promising aspect of this FEG design is the inherent ability to scale to large sizes. The United States Army Space and Strategic Missile Defense Command fact sheet for high energy density ferroelectric ceramics for explosive pulsed power applications lists achievable specific energy from these generators from 1.5-2.5 J/cc depending on load configuration.(6) If we pick a value mid way between the range quoted in reference 6 for illustration purposes, we can get some idea of energy scaling for this design FEG. Note that with cylindrical symmetry, it is easy to place large areas and volumes of material under pressure. Figure 10 illustrates the scaling principles that would be applied to this design.

OD mm	ID mm	Height mm	Volume Cm^3	Energy Joules
48	**32**	**10**	**10.54**	**21.08**
51	32	10	12.54	25.08
57	34	13	20.84	41.68
64	38	14	28.30	56.60

Figure 10. Scaling data for cylindrical FEG's.

The bolded first line is the current crystal geometry and the energy level that would be obtained at the assumed energy level if optimally matched to a load. Note that in the 3rd line the crystal has been enlarged approximately 20% diametrically but has increased in volume by 100%.

Increasing the OD of the crystals provides two major benefits. The first is that the volume is increasing at a Δr^2 rate and this leads to large increases in volume for small increases in diameter. The second is that it also allows for the ID to be increased. When the ID is increased it allows for a taller crystal due to the standoff necessary for the pressure to decrease to an optimal level. Therefore larger OD's allow for both a thicker wall in addition to a taller cylindrical FEG.

Larger crystals have minimal impact on the waveshaping design. Proper cone angle and standoff distance would remain the same assuming no potting or explosive material changes. Because of the simple waveshaping geometry it is possible to scale these systems to large crystals while minimizing the amount of explosive used.

V. SUMMARY

In this work, we have developed a unique FEG pulsed power unit by focusing on techniques to produce highly controllable pressure pulses from explosives to unique PZT crystals shaped to enhance energy output. This effort has demonstrated implementation of FEG pulse power units in both conical and cylindrical geometry with major success in the cylindrical units. The designs produced are simple, reliable, robust, and easy to fabricate. The technology is inherently rugged and has the ability to produce large amounts of energy due to large volumes of material that can be pressurized using small amounts of explosive material. While we have not tested to the energy levels suggested in figure 10, it seem likely that the methods presented here will favorably scale to larger geometries and make possible the development of FEG's that can produce these high energy levels.

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